Time simulation of segmented reflector telescopes in multidisciplinary analysis

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INTRODUCTION

NASA has an ambitious plan for exploring the universe involving many space-based observatories. The CSI program (Control Structure Interaction) is a NASA funded project to design microprecision spacecraft observatories from a multidisciplinary approach by integrating the structural, control and optical subsystems of these spacecraft. A Focus Mission Interferometer (FMI), representative of one of NASA's astrometric missions for extrasolar planet detection was selected as the focus for developing this multidisciplinary technology. Very early in this study it was discovered that integrated modeling tools were necessary to predict the on orbit performance of the FMI.

In its original incarnation, the optical train of the FM I extends over a flexible truss nearly 30 meters in length, on which is mounted siderostats, several folding and fast steering mirrors, combining optics, and optics for metrology. The optical pathlength difference between stellar light collected at siderostat pairs must be maintained to a tolerance of the order of several nanometers through the optical train. This precision is achieved via a multilayer design architecture concept, combining vibration isolation, structural quieting, and a three tier control system for commanding the optical elements. The need to study the complex effects of dynamic and quasistatic disturbances such as reaction wheel imbalances, tape recorders, and thermal gradients within this architecture led to the development of the modeling tools COMP (Controlled Optics Modeling Package) and IMOS (Integrated Modeling of Optical Systems).

IMOS is composed of several interconnected discipline modules with COMP serving as the central optical module. COMP'S optical capabilities are quite extensive [1], and was specifically designed to be compatible with structural and control models. This is accomplished by using global coordinate systems to characterize the optical elements. Global coordinates used in conjunction with optical sensitivity matrices derived from COMP's differential ray trace routines, allows the analyst to build linear state space models within IMOS for system level design and performance evaluation. IMOS currently incorporates several other modules, including a finite element modeling capability from which system design level models can be constructed (rod, beam, plate elements, rigid masses), a thermal module for conductance and radiative heat transfer analysis, and also all of the control design, analysis, and simulation functions and tool boxes contained in MATLAB.

Although the interferometer application spurred much of the development of these tools, IMOS and COMP are broadly applicable to many optomechanical systems. COMP has been applied to such missions as the Hubble Space Telescope (HST), the Space IR Telescope Facility (SIRTF), and the Submillimeter Moderate Mission (SMMM). Applications of COMP to these missions include the prescription retrieval problem for the HST, an analysis of the fine guidance sensor for SIRTF, and the design and analysis of a figure control system for SMMM. IMOS has been used to analyze the effect of thermal gradients on optical performance of the Submillimeter Intermediate Mission (SMIM), to determine the optimal placement of damping elements on the support backup structure of SMIM, and for establishing requirements for adaptive optics systems for a representative class of moderately sized optical telescopes.

The interconnection of these modules under the IMOS umbrella leads to a powerful tool for doing end-to-end design and simulation of complex integrated optomechanical systems. This paper describes several of the capabilities of IMOS. The design and analysis of a Segmented Reflector Telescope (SRT) will serve as the model for the paper. The use of IMOS in obtaining the optical layout and developing the structural model will first be discussed. This will be followed by several examples illustrating how IMOS can be used in the analysis and compensation of dynamical effects on the optical performance of the SRT.

2. SYSTEM LEVEL DESIGN

The segmented reflector telescope (SRT) model is an f/10 segmented mirror Cassegrain telescope system. The finite element model is "rubberized" in the sense that the number of rings and size of panels can be varied with minimal effort. The model in this study is a two-ring, 18 segment primary mirror with a 3.75 meter aperture. The primary mirror support truss is a tetrahedral structure with parabolic shape. The primary mirror segments are hexagonal, and are modeled as 3 very stiff rods, so the size of the "panel" does not change during deflections (the orientation of the"panel" will change). The secondary mirror is modeled as a concentrated mass attached to the outer ring of the primary mirror support truss by a 3 rod spider support. When the truss is attached to ground at 3 of its center nodes, the resulting finite element model has 291 degrees of freedom with a fundamental frequency ~15 Hz. (See Fig. 1 and Fig. 2).

The finite element model was built to be flexible, in that the size of the model (i.e. the number of rings, size of panels, shape of primary mirror, etc.) can be easily modified and the structural model can be parametrically updated. This is of tremendous use in the early stages of development to quickly answer "what if" questions for various design configurations. Also, this type of flexibility is absolutely essential for design optimization.

3. BENEFITS OF PASSIVE DAMPERS

This example demonstrates how IMOS can be used to analyze and compare the benefit of using passive dampers in different configurations to attenuate disturbances in the optical train of the SRT. The disturbance is the output of a sixth order Butterworth filter with a 100 Hz cutoff, which was injected into the system through the nodes attached to ground. This introduces a fairly rich disturbance as the model possesses eighteen modes below the neighborhood of the cut off frequency.

A wavelength of 100 urn was used. The exposure time for each of the intensity functions presented here is 1.5 seconds. Since images are taken over a finite time length, it is important to simulate the actual time length of the image capture to compare and contrast different designs. While comparing instantaneous images may show little difference between different designs, time integration may show a significant difference between designs.

Three different configurations are analyzed here. The first uses passive dampers placed in locations which maximize the strehl ratio, a measure of the point spread intensity at focus. The second uses passive dampers placed in locations which minimize the RMS deflections of the primary mirror truss structure. The third uses no passive dampers. A more detailed description of these configurations can be found in Ref 2.

The results are shown in Fig. 3-5. As expected, the passive dampers greatly improve the quality of the image. Fig. 3 shows the intensity profile of the image with no dampers in the structure. While a sharp central peak appears, there are a large number of ripples (hence photons) around the periphery of the central peak. Fig, 4 shows the intensity profile of the image with the RMS optimized dampers in the structure. More photons are concentrated in the center of the intensity function. Fig. 5 shows the intensity profile of the image with the strehl ratio optimized dampers in the structure. This image also shows a fairly clean central spike with only a minor amount of ripples around the periphery of the central peak. However, a comparison of Fig. 4 and Fig. 5 shows that the central peak using the strehl optimized damper locations is narrower and taller than the central peak using the RMS optimized damper locations.

These results clearly show that an integrated criteria, modifying the structure to maximize optical performance, allows one to obtain better performance than using only a structural criteria.

3. SLEW AND SETTLE

When a telescope is in space, it is desirable to maximize the percentage of time actually spent observing science objects, such as stars or planets. It takes time for the spacecraft to slew to the new observing area and find the star. Once the star is found, it takes time for all the vibrations of the structure excited during the slew to die out, so a clear image can be formed with the telescope. This example demonstrates how the optics come into alignment, (the image comes into focus), as the structural vibrations die out.

Fig, 6-10 are a progression of instantaneous intensity functions (images) that occur as the spacecraft settles after a slew maneuver. Fig. 6 shows the image initially coming into focus, The central peak can just be resolved. Fig. 7 shows an increase in the central peak, and the corresponding decrease in side lobes. Fig. 8 shows the optics in alignment, with the best intensity function obtainable with this optical system. Fig. 9 shows the image a short time later. The intensity function has worsened, due to control system overshoot. Finally, Fig. 10 shows the peak intensity after settling has occurred.

The ability to visualize the end-to-end process, the structural vibrations causing disturbances to the optical image, is a valuable tool in understanding when the actual imaging can begin. The image integration overt time would predict the imaging performance of the system as a function of the jitter it is subjected to.

4. BINARY STAR RESOLUTION

This example demonstrates the benefits of simulating the entire exposure time. Imaging double stars places additional requirements on telescope stability because of the close proximity of the two stars. This example uses reaction wheel disturbances on a spaceborn telescope. Two different cases are shown, the first uses no structural dampers, and the second uses 6 passive dampers whose location is based on the strehl optimization criteria.

Fig. 11 and Fig. 12 show a very short time exposure intensity function of a double star. Both stars are resolvable with dampers, and with no dampers. Close inspection shows that the intensity function of the structure with dampers, shown in Fig. 11 is slightly taller and narrower than the intensity function for the structure without dampers, shown in Fig. 12. From these two short exposure images, there appears to be no justification for adding passive dampers to the structure.

However, if the exposure time is increased, as shown in Fig. 13 and Fig. 14, the two stars are no longer resolvable in the structure with no dampers. This behavior is reminiscent of short and long exposure MTF's of the optical system in the atmosphere. With no dampers in the structure, the reaction wheel disturbances are not damped out as well. The increased magnitude of disturbances cause the peaks to be slightly wider. The peaks also move around in the focal plane slightly more. Over time, this causes an averaging of the distribution of photons on the focal plane, and this causes the two stars to become indistinguishable. The ability to do end-to-end time integrated modeling is extremely beneficial in this example.

5. CONCLUSIONS

Several capabilities of IMOS and COMP have been demonstrated in the paper. The breadth of these applications extend from the definition and wedding of the optical layout and structural design to the optimization of the placement of damping elements in the structure to maximize image quality. IMOS provides an integrated environment for analyzing the system level effects on optical performance of important internal and external system disturbances due to dynamic and thermal distortions. Here several options are available for evaluating optical performance; including the use of spot diagrams, PSF's, strehl ratios, and OPD maps. Between the system input and output ports, IMOS can also be used to assess (and eventually optimize) design trades between various subsystem designs. Comparisons between and optimization of candidate optical layouts, mechanical designs, and control system designs can be conducted within IMOS.

The benefit of conducting design and analysis in this integrated fashion was clearly illustrated in the binary star example. Here the effect of the design change introduced by the addition of damping elements was traced through the telescope as it was subjected to dynamical disturbances from reaction wheel imbalance. The results clearly showed that the images formed from the telescope with optimally placed dampers in its backup truss could easily distinguish the binary star system, while the telescope without dampers could not.

Additional capabilities are being added to the modeling tools. Some of these include polarization effects in COMP, and additional elements in the structural and thermal modules of IMOS. On a broader scale it is currently envisioned to add an optimization module to IMOS, attach modules for the analysis of adaptive optics systems by including wavefront sensor models and focal plane detector models, etc.

IMOS can be obtained for a small fee through COSMIC. To obtain these programs, contact COSMIC at (706) 542-3265, or write COSMIC, The University of Georgia, 382 East Broad Street, Athens, GA, 30602. They can also be reached via Internet as service@cossak.cosmic.uga.edu. Ask for programs NPO/1 8925/8507 and NPO/1 8926/8508. You will get a distribution tape with executable, source, and example files and a manual.

A Support Desk has been established at JPL to provide assistance in using IMOS. The Support Desk will help in installing the programs, making system models, and interpreting the results. If you have problems, or wish to request new technology additions, these should be reported to the Support Desk. Phone (818) 354-8471, or imos-support@csi.jpl.nasa.gov.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

(1) David Redding, Laura Needels, Kent Wallace, and Marty Levine. "Controlled Optics Modelling Package User Manual". JPL D-9816. June 1, 1992.

(2) Mark Milman and Laura Needels. "Modeling and Optimization of a Segmented Reflector Telescope", SPIE Conference, Albuquerque, New Mexico, February, 1993.

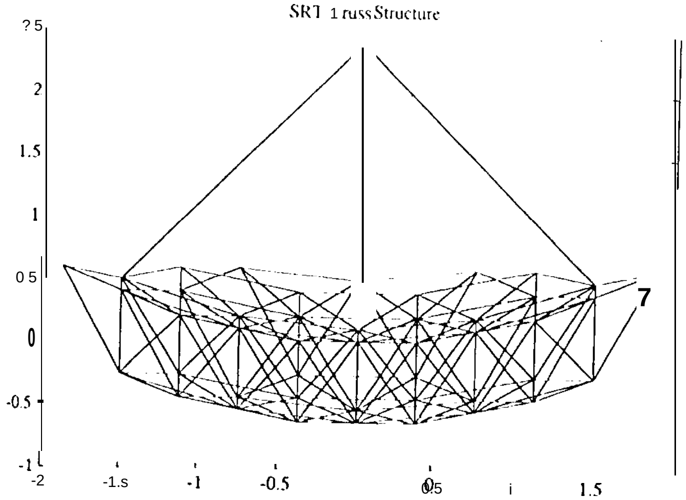

Figure 1

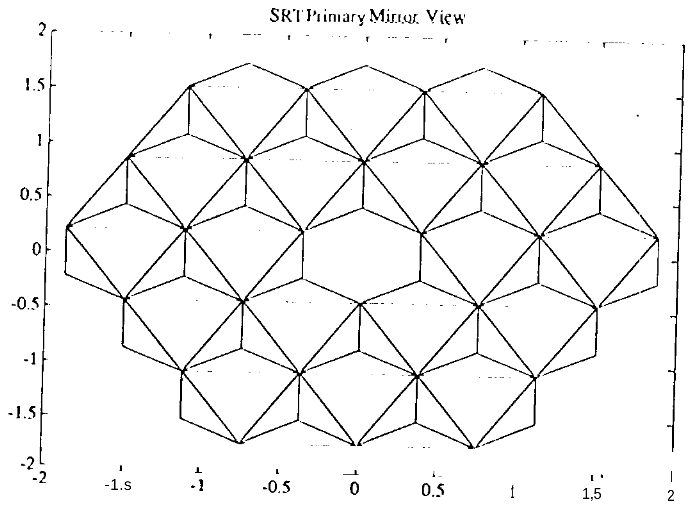

Figure 2

Intensity Function-1.5 Seconds Integration-No Dampers

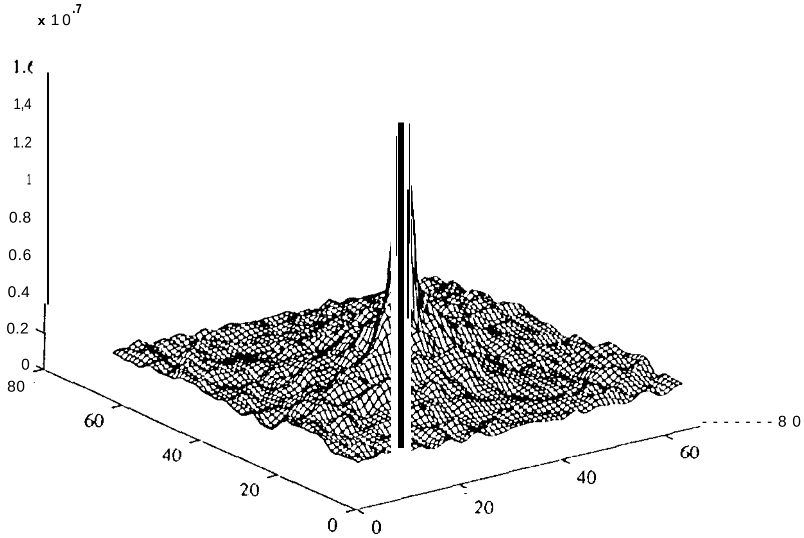

Figure 3

Intensity function- 1.5 Seconds Integration-RMS Dampers

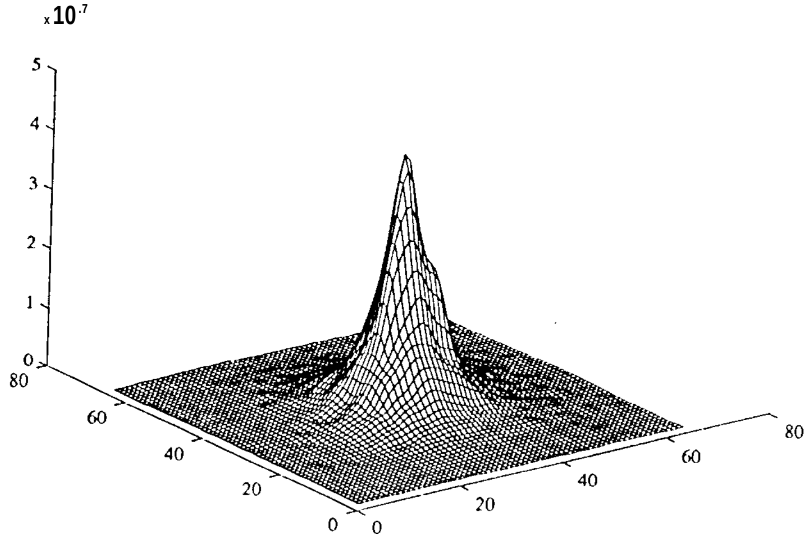

Figure 4

Intensity Function- 1.5 Seconds Integration-Strehl Dampers

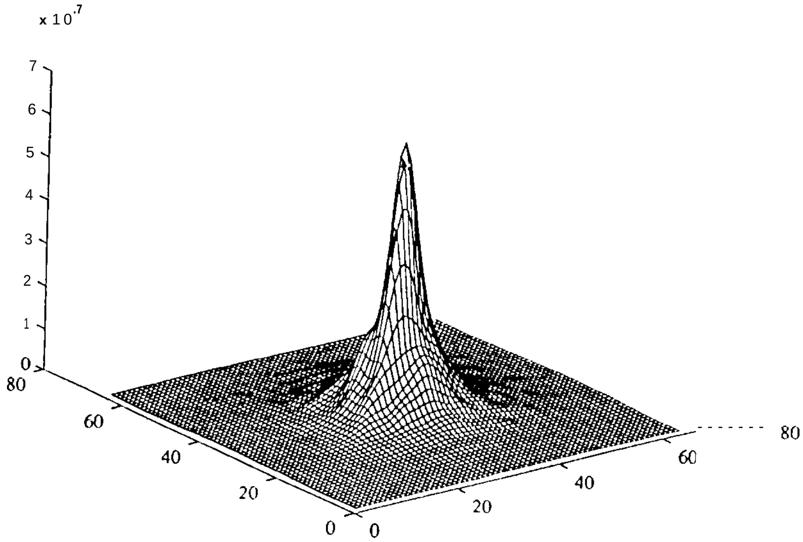

Figure 5

Slew & Settle - Image Coming Into Focus

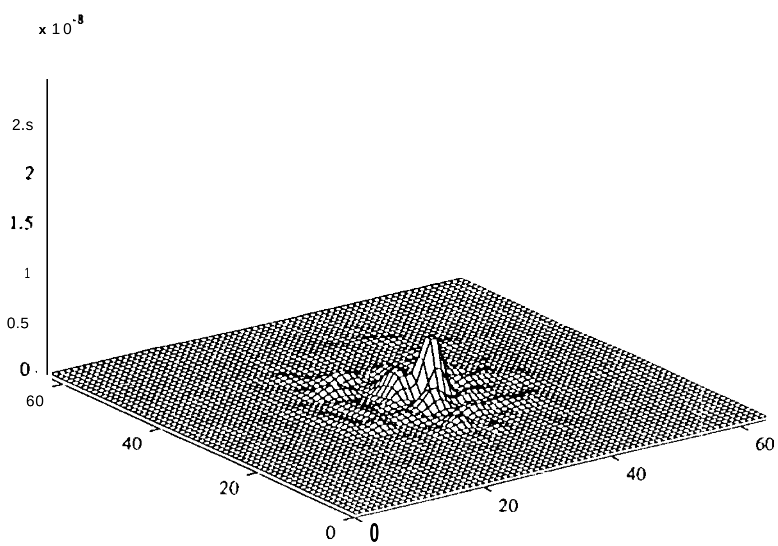

Figure 6

Slew & Settle - Central Intensity Increasing

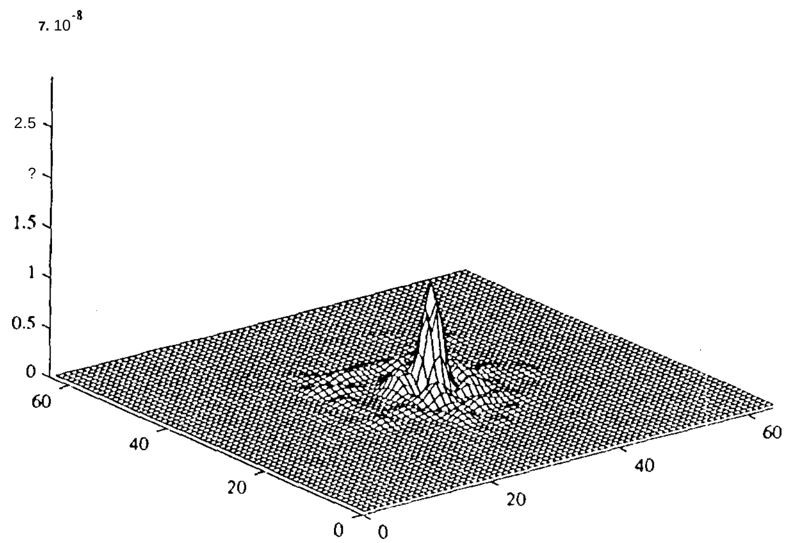

Figure 7

Slew & Settle- Optics in Alignment

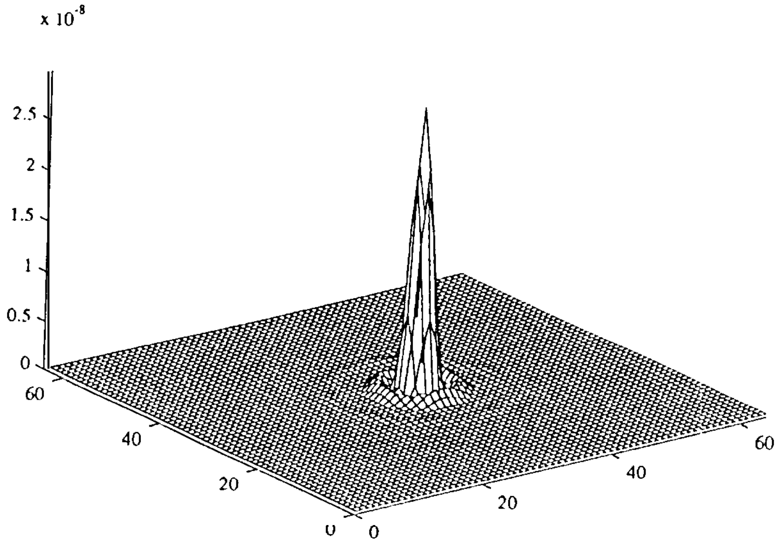

Figure 4

Slew & Settle- optical Misalignment From Overshoot

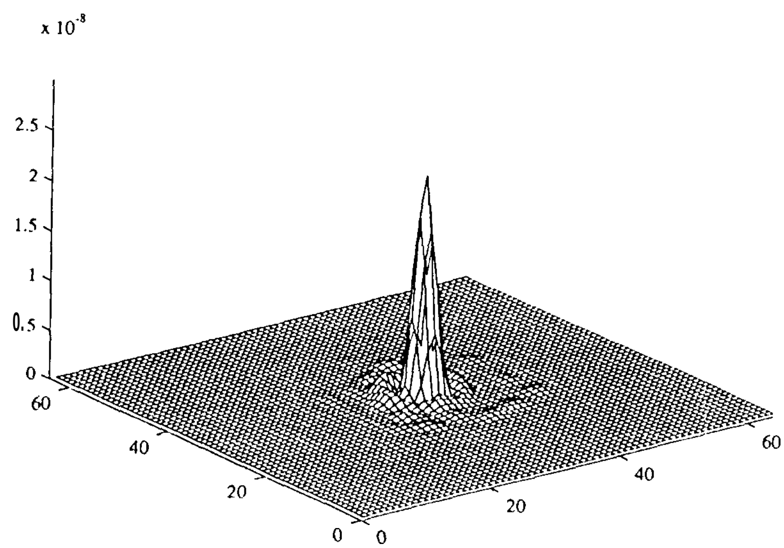

Figure 9

Slew & Settle- Peak Intensity After Settling

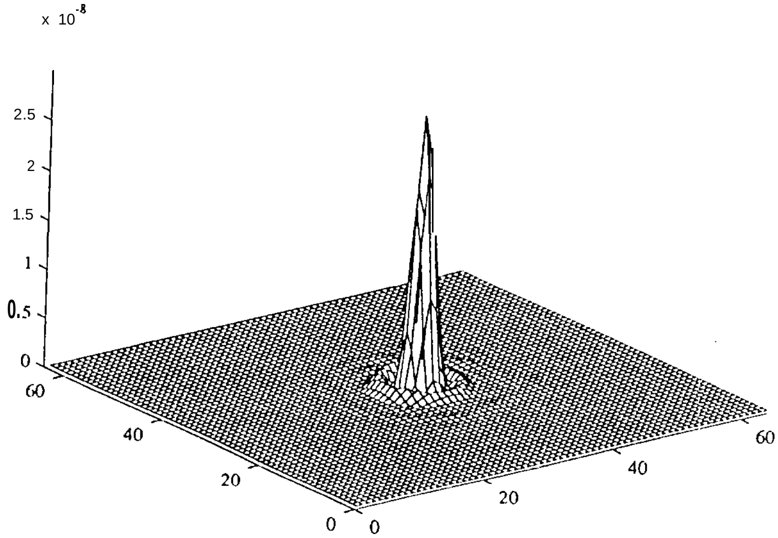

Figure 11b

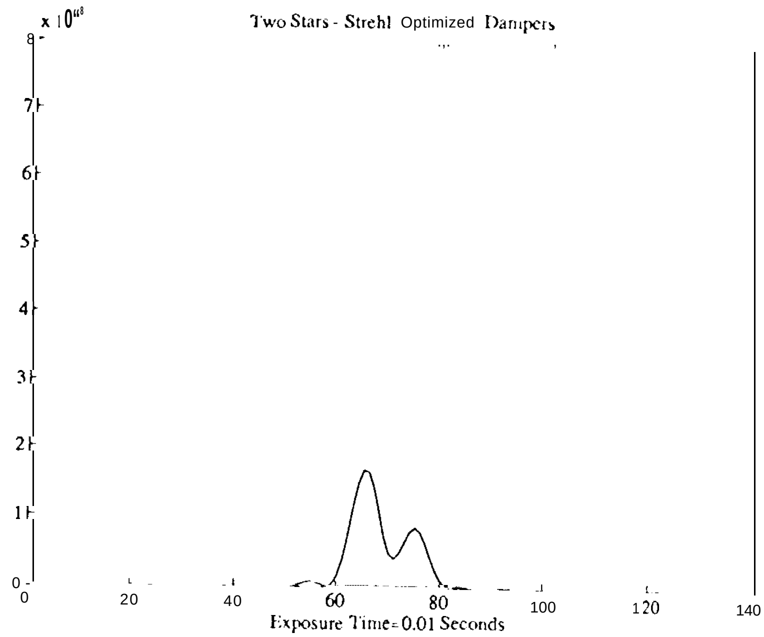
x 10^-3
Two Stars - Strehl Optimized Dampers
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
Exposure Time=0.01 Seconds

Figure 11

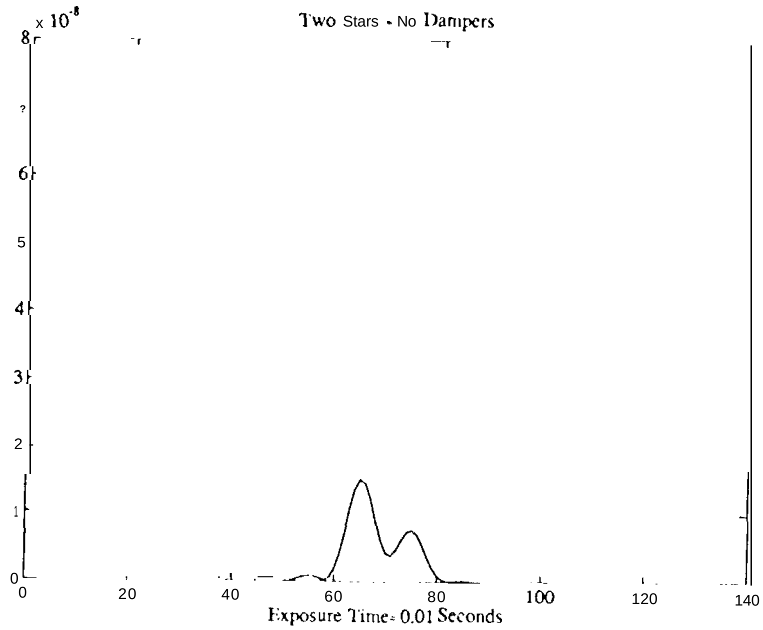
Two Stars - No Dampers
x 10-8
8
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
Exposure Time= 0.01 Seconds

Figure 12

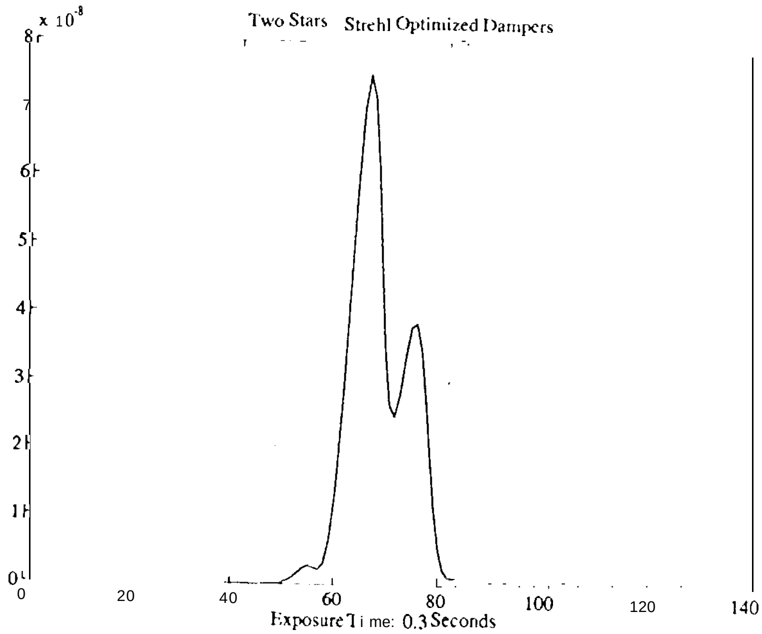
Two Stars Strehl Optimized Dampers
x 10^-8
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
Exposure Time: 0.3 Seconds

Figure 15

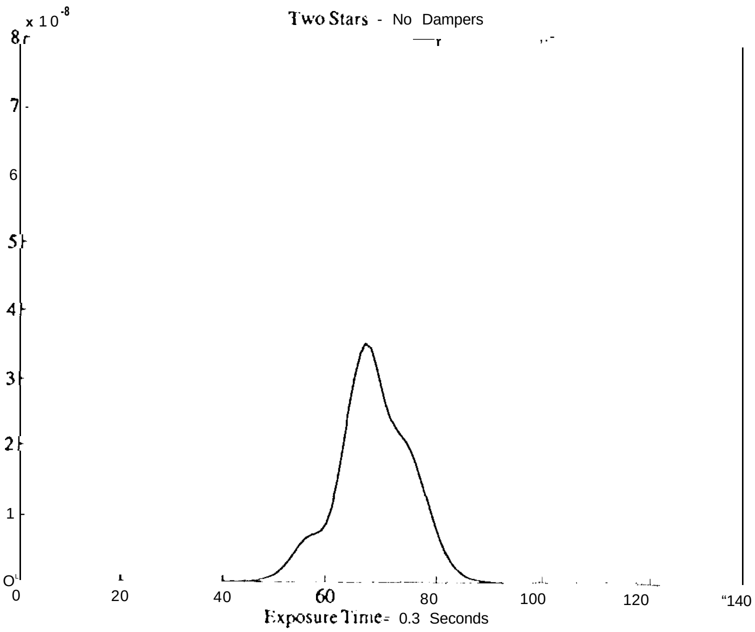
Two Stars - No Dampers
x 10^-8
8
7
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
Exposure Time= 0.3 Seconds

Figure 14